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Scenario Analysis and the Economic and Financial Risks from Climate Change

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Abstract

Central banks are increasingly focused on the risks from climate change for the economy and financial system. Two sets of risks are of particular concern: physical risks from more frequent and severe weather events, and transition risks from the move toward a lower-carbon intensive economy. This paper adapts climate-economy models that have been applied in other contexts for use in climate-related scenario analysis. We consider illustrative scenarios for the global economy that could generate economic and financial system risks by varying assumptions on key variables such as climate policy in plausible ways. The results show significant economic implications from climate change and the transition to a low-carbon economy. The timing and magnitude of global GDP and sectoral impacts, among other outcomes, vary considerably under the mix of scenarios. These risks touch on the interests of a broad range of stakeholders across the private and public sectors. In addition to central banks and governments, these risks could affect financial institutions, resource-intensive industries and other private sector firms. Further improvements in scenario analysis, as well as wider-spread use across the public and private sectors, could lead to a better understanding of the risks and opportunities of climate change.

Topics: Climate change; Economic models; Financial stability; International topics

JEL codes: C68, D58, E50, O44, P18, Q4, Q54, Q55

Résumé

Les banques centrales se focalisent de plus en plus sur les risques que les changements climatiques font peser sur l'économie et le système financier. Deux types de risques retiennent particulièrement leur attention : les risques physiques découlant de phénomènes météorologiques plus fréquents et plus violents, et les risques liés à la transition vers une économie sobre en carbone. La présente étude vise à adapter, pour l'analyse de scénarios liés au climat, des modèles climat-économie ayant servi dans d'autres contextes. Nous étudions des scénarios indicatifs de l'économie mondiale susceptibles de générer des risques pour l'économie et le système financier en faisant varier, de façon plausible, différentes hypothèses concernant des variables clés comme les politiques climatiques. Les résultats font apparaître d'importants effets économiques découlant des changements climatiques et du passage à une économie sobre en carbone. L'ampleur des répercussions sur le PIB mondial et les secteurs d'activité, et le moment où elles se font sentir, entre autres conséquences, varient sensiblement selon les divers scénarios considérés. Ces risques touchent les intérêts d'un large éventail de parties prenantes dans les secteurs public et privé. Outre les banques centrales et les gouvernements, ces risques pourraient avoir une incidence sur les institutions financières, les industries à forte intensité de ressources et diverses entreprises du secteur privé. De nouveaux progrès dans l'analyse des scénarios, ainsi qu'un recours plus généralisé à cette analyse dans les secteurs public et privé, pourraient permettre de mieux comprendre les risques et les occasions qu'entraînent les changements climatiques.

Sujets : Changements climatiques; Modèles économiques; Stabilité financière; Questions internationales

Codes JEL : C68, D58, E50, O44, P18, Q4, Q54 et Q55

Introduction

Climate risks and central banks

Central banks are increasingly focused on the risks from climate change for the economy and financial system. While setting environmental policy is the job of governments, climate change can affect the ability of central banks to achieve their financial stability and inflation-targeting goals. Two sets of risks are of particular concern:

- **Physical risks** from more frequent and severe extreme weather events (Trenberth, Fasullo and Shepherd 2015). Severe weather can cause considerable economic disruptions and losses to the financial system through both insured and uninsured losses.
- **Transition risks** from the move to a lower-carbon economy. Changes in consumer and investor preferences, as well as government policies to make pollution more expensive, could result in important economic shifts. If these are sudden or unexpected, they could pose financial system risks—for example, by stranding assets through unanticipated writedowns in carbon-intensive industries. At the same time, green industries could see new growth opportunities. This could result in complex reallocations of workers and assets across the economy.

Climate change and climate policy could also have a potential impact on key economic variables relevant to monetary policy. These include investment, labour productivity, inflation and the neutral rate of interest.

In Canada, climate risks are a particular concern for two reasons. First, energy and other carbon-intensive sectors play a large role in the Canadian economy. Second, as a small open economy that exports a lot of energy products, Canada is vulnerable to shifts in pollution policy and preferences of its trade partners.

While central banks are concerned with climate change, their current economic models and tools were not designed to incorporate the effects of climate change. This poses challenges to assessing the many channels through which climate change could affect the economy and financial system. Compounding this challenge is the considerable uncertainty over future developments in policy, technology, the natural environment and other key factors related to climate change.

Central banks are not alone in these challenges. Private sector financial institutions are also increasingly examining the implications of climate change to better understand both the opportunities and the risks. This research can inform strategic plans and promote resilience.

Some central banks and private financial institutions have started developing tools and inputs for using scenario analysis to better understand climate risks (e.g., the Bank of Canada currently participates in the Network for Greening the Financial System [NGFS] sub-group on scenario analysis; see also TCFD 2017 and Bank of England 2017). Scenario analysis examines plausible future states of the world and forecasts situations that *could* happen rather than predicting what *will* happen. It can help users evaluate a range of hypothetical outcomes based on different assumptions of what may occur (see **Box 1**).

Scenario analysis is particularly useful for climate change, where the evolution of key variables is uncertain. Consistent with standard practice in financial system stress testing, these scenarios should be extreme yet plausible to be the most useful and give a sense of the full distribution of possible risks.

The NGFS is developing an analytical framework for assessing climate-related risks to gauge the impact of these risks on the economy and financial system. Scenario analysis will play a key role in the framework. The NGFS is working toward a standardized set of climate-related scenarios for scenario analysis by central banks and others (NGFS 2019). The Bank of Canada is contributing to this work and hopes to leverage this and its own internal modelling in developing Canada-specific scenario analysis to inform monetary policy and support financial system stress testing.

Box 1: This study is not an assessment of policies for fighting climate change

Setting environmental policy is the job of governments. Policies to prevent global warming—such as carbon taxes, emission caps and spending on technological development—fall outside the mandates of central banks. In that spirit, this paper does not provide a cost-benefit analysis of specific climate-change policies. To do so would require a different modelling framework than presented here (discussed in more detail in the "Related literature" section). It would also require a set of considerations beyond the Bank of Canada's mandate.

In particular, illustrative carbon price paths shown in the results section are model estimates of a global "shadow price" for reducing emissions. These are model constructs necessary for simplifying what could be a broader range of climate-policy actions. As model constructs, they should not be confused for advice by the authors on any preferred paths for carbon prices globally or in Canada. The price paths are also not forecasts or estimates of future prices; policy actions could take a variety of forms and strength and are unlikely to be exclusively in the form of carbon prices. The paths are consistent with other estimates found in past studies using similar modelling approaches (see "Robustness Check").

The analysis in this study is geared toward understanding economic and financial risks related to climate change, and our results show that these exist under any set of policy choices (see **Figure 4**). Our goal is to better understand what this distribution of risks means for the economy and financial system and for the ability of central banks to achieve their inflation targets.

Scenario analysis in this study

This paper contributes to efforts to better understand climate-related risks by adapting climate-economy models to clarify potential sources of economic and financial risks. It does so in three ways:

- We provide an overview of the main modelling approaches related to the economics of climate change.
- We craft examples of the types of scenarios that could generate economic and financial risks. We do this by varying assumptions on key variables, such as climate policy, in plausible ways.
- We use a computable general equilibrium (CGE) model to assess the economic impacts of these scenarios. This also provides insights into potential financial system risks.

While the literature is rich with economic assessments of various climate policies, this study is among the first to craft illustrative climate policy pathways and assess their distribution of transition and physical risks on the macroeconomy.

This paper shows that combining several climate scenarios with existing climate-economy models can provide useful insights on the distribution of risks for the global economy and financial system. Our illustrative results suggest there are significant economic risks surrounding climate change and the transition to a low-carbon economy. The timing and magnitude of global and sectoral impacts on gross domestic product (GDP), among other outcomes, look considerably different across the mix of scenarios. The results also suggest that although transition risks can be avoided through inaction, this comes at a significant economic cost (measured in terms of output) through higher physical damages and risks. Action that comes late (as proxied by the introduction of carbon taxes) must be more abrupt to keep temperature increases in check, which raises transition risks. Earlier action also allows more time for new technologies to enter the market in response to price signals, leading to a larger green energy sector and lower transition costs.

The paper is structured as follows. In the first section, we provide an overview of the literature assessing the economic impacts of climate change and climate mitigation, including past studies using scenario analysis. Next, we describe the main model used in this paper, the MIT Economic Projection and Policy Analysis (EPPA) model, and then outline a set of illustrative scenarios used in this study. In the remaining sections, we share illustrative results before concluding with a discussion of the implications for future work.

Related literature

The literature exploring the effects of climate change on the economy can be largely partitioned into three categories: the impact of rising temperatures (i.e., physical risks); the impact of transitioning to a low-carbon economy (i.e., transition risks); and, to a lesser extent, the crafting of scenarios for economic stress testing. The remainder of this section goes into more detail about each of these three categories.

Physical risks

Assessing the economic impact of climate change has mostly relied on the use of integrated assessment models (IAMs) that seek to capture the relationship between temperature and GDP over the long term (Nordhaus 2017). IAMs have been extensively used by international organizations and national governments to support the development of climate policy, including in determining the appropriate price of emissions. Some IAMs, such as the Dynamic Integrated Economy Climate (DICE) model, are compact, with little regional and sectoral disaggregation, but they are highly transparent. Others, such as the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and the Policy Analysis of the Greenhouse Effect (PAGE) models, provide regional and sectoral detail and enable a picture of distributional impacts of climate change. The greater level of detail means these models are somewhat less transparent in their calculation of damages.[1]

IAMs can provide valuable insights into the climate–economy relationship and shed light on the methodologies governments use to set climate policy. IAMs provide nuanced information on the natural environment that can help inform assessments of physical risks. For example, IAMs allow us to assess the negative macroeconomic impacts from a greater incidence of climate-related disturbances that reflect events such as extreme heat waves, rising sea levels and drought (Ceronsky et al. 2011). Moreover, IAMs

[1] For more information on these models, see FUND and PAGE.

allow users to estimate carbon prices under different policy regimes, which can be useful for assessing transition risks.

As with all models, IAMs have drawbacks. First, IAMs can sacrifice regional and sectoral detail in favour of expanded information on the climate side. These missing details can be important when looking at transition effects from climate policy. Second, IAMs lack detailed representations of the economy and financial system and do not currently include fiscal and monetary policy responses that could provide counterbalancing effects on the economy. Finally, IAMs have parameters where the underlying relationships are not well understood. These parameters include the relationships between emissions and temperature and between rising temperatures and economic impacts (i.e., what is referred to as the "damages function").

Transition risks

Analyzing the transition to a low-carbon economy requires rich detail about the economy at the regional and sectoral levels. While several studies have employed IAMs for this purpose (Fawcett et al. 2015; Meinshausen, Raper and Wigley 2011; Akimoto, Sano and Tehrani 2017), most of the work to date has relied on structural models such as CGE models (examples discussed below). CGE models typically account for how economic activity drives emissions, and they do so with a high level of granularity across sectors (including within the energy sector) and in terms of inputs (e.g., capital, labour and technology). These attributes of CGE models provide insights into how climate policies can affect economic activity.

Unlike IAMs, however, CGE models cannot measure an economy's reaction to rising temperatures (i.e., they show no physical damages to the economy from temperature and weather changes). Therefore, these models may underestimate the economic benefits from policy actions to stop climate change. This limits their usefulness in assessing the trade-offs of policy action on climate change versus non-action in a stand-alone way. Other attempts to assess this trade-off suggest mitigating climate change has strong economic benefits (Tol 2018); and estimates from the broader literature show a negative link between global warming and GDP. This can be seen in **Chart 2-A** of **Box 2**. In addition to being silent on physical damages, CGEs are often built on a recursive dynamic framework. This means economies fail to react in advance to pending climate policies because economic agents lack foresight.

A large literature employs CGEs to investigate transition risks associated with international climate accords. These studies vary in terms of models and scenarios (for a review, please see Liu et al. 2019). On the modelling side, they include the MIT EPPA model used in this study (see details below), the G-Cubed model and the Global Trade Analysis Project (GTAP) model. These studies also use a series of more regionally focused models.[2] In terms of scenarios, some have modelled country-level pledges submitted to the United Nations Framework Convention on Climate Change (UNFCCC) as part of their Paris Agreement commitments (McKibbin, 2015a, 2015b; Vandyck et al. 2016). Others have used emissions profiles consistent with the Paris target of limiting warming to 2°C to craft scenarios (Kompas, Pham and Che 2018; van Vuuren et al. 2011), with particular emphasis on energy transition (Vandyck et al. 2016).

[2] These include including the Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model, the General Equilibrium Model for Economy – Energy – Environment (GEM-E3) and the SAGE Computable General Equilibrium model built by the United States Environmental Protection Agency. For more information, see MIT EPPA, G-Cubed, GTAP, AIM/CGE, SAGE, and GEM-E3.

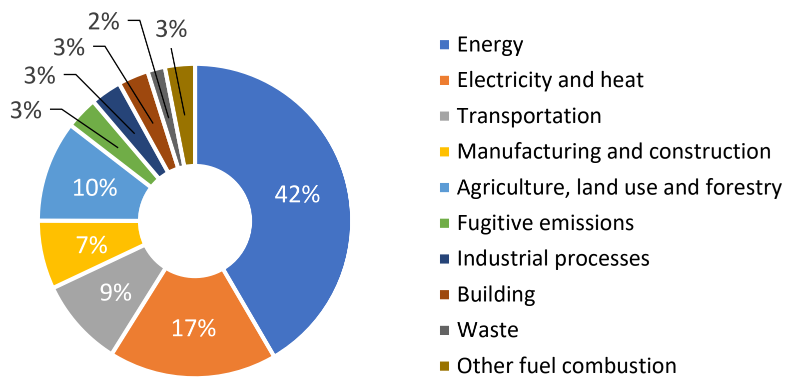
An additional body of literature uses CGE models to examine the efficacy of different policy schemes, such as carbon tax, cap-and-trade and emissions control (Fujimori et al. 2016). Typically, these applications of CGE models have focused on assessing the suitability of various policy choices, and not on economic and financial system stress testing.

Scenario-analysis studies

Given the uncertainty over forecasting scenarios decades into the future, studies have focused on a range of scenarios. This is in contrast to the usual practice in macro stress testing of using one scenario.

Studies looking at the physical impacts of climate change have used scenarios with output from global climate models that show the response of the Earth's temperature to greenhouse gas (GHG) concentrations. Representative Concentration Pathways (RCPs), a type of scenario used by the Intergovernmental Panel on Climate Changes (IPCC), have provided the basis for examining physical risks in several studies.[3] This approach was adopted by the IPCC in its *Fifth Assessment Report* (AR5).[4] Scenarios looking at transition risks have meanwhile focused on the energy, electricity and heating sectors due to their contribution to global emissions (**Chart 1**). Namely, the International Energy Agency's Sustainable Development Scenario (SDS)[5] and the International Renewable Energy Agency's Renewable Energy Roadmaps (Remap programme)[6] provide detailed energy-transition scenarios.

Chart 1: **Global greenhouse gases emissions by sector in 2016**



Source: World Resources Institute Climate Analysis Indicator Tool, 2019

Central banks and private financial institutions are also increasingly crafting narratives for scenario analysis. Of note, the NGFS has a sub-group dedicated to scenario analysis.[7] Furthermore, the Task Force on Climate-Related Financial Disclosures (TCFD) has called on firms to use scenario analysis and stress testing in the context of quantifying risk exposure related to climate change (for a review, see TCFD 2017).

[3] For more information on the scenarios and applications in the literature, please refer to the Represented Concentration Pathway database provided by the International Institute for Applied Systems Analysis.

[4] Please refer to section SPM 2.1 of IPCC 2014a.

[5] The IEA's Sustainable Development Scenario (SDS) outlines a plausible transformation of the global energy system to 2050 in order to achieve significant emissions reductions within the energy sector (IEA 2019).

[6] The International Renewable Energy Agency's (IRENA's) Renewable Energy Roadmaps outlines the potential for countries to reduce energy-related emissions by scaling up renewables through 2050.

[7] More information on the Network for Greening the Financial System can be found on the NGFS website.

In light of this, the Bank of England (2019) has recently published a how-to guide on exploratory scenarios, and it is looking to provide macrofinancial data for private-sector scenario analysis. Furthermore, DeNederlandscheBank has recently published results from a stress test focused on energy transition in which it considers a mixture of policy and technology shocks. This work identified sectors within the Netherlands most at risk in the transition toward a low-carbon economy (Vermeulen et al. 2018). The Bank for International Settlements has also released a report on central banking and climate-scenario analysis, highlighting many of the modelling issues and sources of uncertainty related to scenario analysis discussed in this paper (Bolton et al. 2020).

The literature on crafting scenarios for economic and financial system stress testing is limited to a taking stock of key questions and considerations. While few specific scenarios are provided, in the literature it is argued argue that a comprehensive analytical framework is required to assess the potential impact of physical and transition risks for financial stability. Work to date has focused on two important dimensions to consider when crafting scenarios: climate policy and the timing of the policy. However, other dimensions could also pose risks, including unexpected changes in consumer or investor preferences, or in technology (Campiglio et al. 2018). While not explored in detail here, an example of how technological changes could shift the balance of risks is provided in **Box 3**.

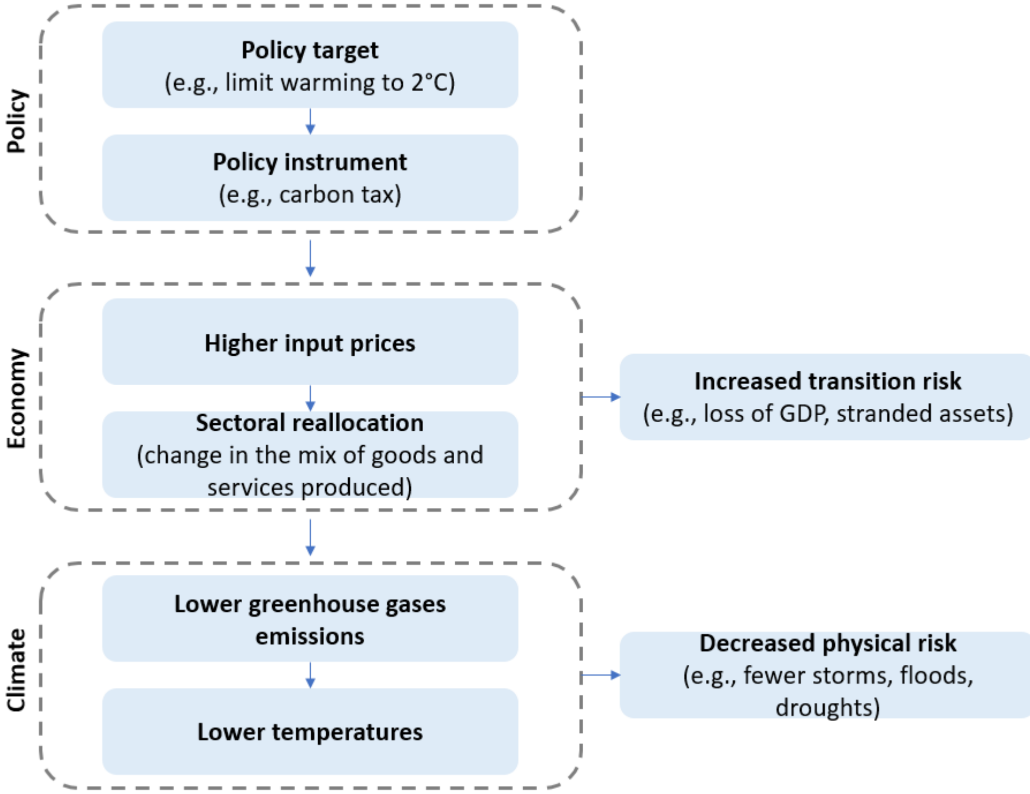
Methodology

Relationship between policy, the economy and climate

We illustrate the relationships between climate policy, the economy and global temperatures assumed in this study in **Figure 1**. Policy-makers set a temperature target to limit warming (e.g., by 2°C), which in turn requires reductions in GHG emissions. To reduce GHG emissions, policy-makers implement policies that can take a variety of forms; for this study, we employ a carbon tax where the revenues are recycled back to households.[8] By raising the cost of using emissions-intensive inputs (i.e., fossil fuels), a pollution charge increases the cost of producing carbon-intensive goods and services. Those cost increases provide an incentive for companies to manufacture their products with fewer emissions. It would also promote growth in alternative sources of energy that are low- or zero-emission. Higher production costs also lead to higher prices for emission-intensive goods and services, encouraging households to switch to lower-emission products. Together, these influences drive the transformation toward a lower-carbon economy, providing the basis for assessing transition risks from climate policy. At the same time, the reduction in GHG emissions limits global warming, reducing the physical damages from climate change.

[8] Other mechanisms include emissions caps and tradeable emissions permits.

Figure 1: The relationship between policy, the economy and climate



MIT EPPA model

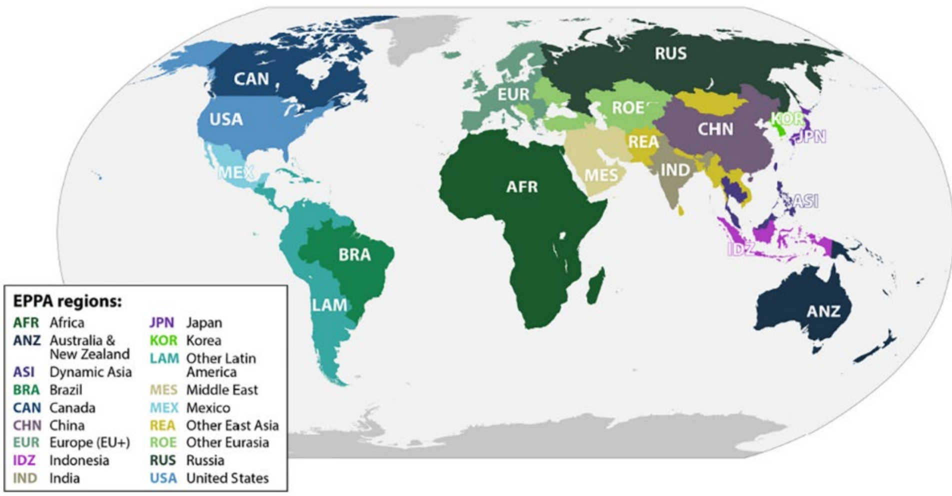
To gain insights into the transition risks from mitigating climate change, this study employs the MIT EPPA model version 6 (EPPA6) (Chen et al. 2015). The EPPA model is a technology-rich dynamic recursive CGE model that captures interactions between all sectors of the global economy, accounting for changes in climate policy. The economic structure within EPPA endogenously evolves according to climate policy and has been extensively used to investigate transitional impacts of climate-change mitigation.[9]

Each region of the world has a set of three economic agents: households, producers and government. Households own primary factors, including labour, capital and natural resources, and provide them to producers. In return, households receive income from the services they provide in the form of wages, capital earnings and resource rents. Welfare-maximizing households allocate income to consumption and savings, pay taxes to the government and receive net transfers from it. Producers transform primary factors and intermediate inputs (outputs of other producers) into goods and services and sell them to other domestic or foreign producers, households or governments. To maximize profits, producers choose a cost-minimizing input bundle of factors and inputs in order to produce goods, a process that evolves endogenously according to technology and market prices. The government collects taxes to finance government expenditures and transfers funds back to households.

[9] For a detailed listing of peer-reviewed articles using EPPA, see the MIT Joint Program on the Science and Policy of Global Change.

Data on production, consumption, intermediate inputs, international trade, energy and taxes for the base year of 2007 are from the Global Trade Analysis Project (GTAP) dataset.[10] The GTAP dataset is aggregated into 18 regions (**Figure 2**) and 33 sectors (**Table 1**), including several advanced-technology sectors estimated with supplementary engineering cost data.

Figure 2: Regions in the MIT Economic Projection and Policy Analysis model version 6 (EPPA6)



The dynamics of the model are driven by a combination of exogenous and endogenous factors. Exogenous factors include reference GDP growth rates, population, technological advancements and resource assets, all by region. In the reference scenario, the factor-augmented productivity levels are adjusted proportionally (Hicks-neutral adjustment) to match that region's assumed GDP growth profile. Dynamics determined endogenously include savings and investment and the depletion of fossil-fuel reserves. Demand for goods produced from each sector increases as GDP and incomes grow, while resource stocks deplete with use, driving up the marginal cost of production. Acting against this, the model incorporates technological advances in production: demand for the output of the technology increases over time, raising the level of investment for operating the technology and thereby reducing the marginal cost of production. Sectors that use renewable resources compete for their availability, generating rents (e.g., land). Together with policy and other constraints, these drivers change the relative economics of different technologies over time and across scenarios, as advanced technologies enter the market only when they become cost-competitive.

Several sectors are explicitly modelled within EPPA, including a detailed representation of energy production. The deployment of new technologies is endogenous. The outputs from traditional (conventional fossil fuel) and advanced generation technologies (e.g., nuclear, hydro, carbon capture and storage [CCS], advanced combined cycle technologies and bioelectricity) are assumed to be perfect substitutes and enter the market when they become cost competitive. Wind and solar, however, are treated as imperfect substitutes due to intermittency from daily and seasonal factors. Technologies are ranked according to their levelized costs[11] of electricity plus intermittency costs for wind and solar. As a

[10] The Global Trade Analysis Project (GTAP) Database contains complete production, consumption, bilateral trade patterns and intermediate use of commodities and services across 140 regions. For more information, please refer to the GTAP 8 Database.

[11] Lifetime costs divided by production.

result, when carbon prices exist, low-carbon technologies are introduced and emissions-intensive capital is decommissioned.

Table 1: Sectors in MIT Economic Projection and Policy Analysis model version 6 (EPPA6)

Sectors	
Crops	Electricity generation:
Livestock	Coal
Forestry	Natural gas
Services	Petroleum
Food processing	Nuclear
Other	Hydro
Transportation (industrial and household)	Wind
Dwelling	Solar
Energy-intensive	Biomass
Energy supply:	Wind combined with gas backup
Coal	Wind combined with biofuel backup
Oil	Coal with Carbon Capture and Storage
Refined oil	Natural gas with Carbon Capture and Storage
Natural gas	Advanced nuclear electricity
First-generation biofuels	Advanced natural gas
Advanced biofuels	
Shale oil	
Synthetic gas from coal	

Scenarios used in this paper

We consider four different scenarios in this paper (**Table 2**) to get a better sense of the distribution of possible risks. The scenarios are primarily based on climatic data from the IPCC Working Group III (WGIII) contribution to the AR5,[12] as well as country-level policy pledges submitted to the UNFCCC as part of the Paris Agreement.[13], [14]

[12] The Intergovernmental Panel on Climate Change's *Fifth Assessment Report* (AR5) is the fifth in a series of such reports that provide a state of knowledge on all matters related to climate change. The AR5 was released ahead of negotiations on reducing carbon emissions at the UN Climate Change Conference in Pairs in 2015, leading to what is now known as the Paris Agreement. Part of the report was dedicated to the "'Mitigation of Climate Change," which presented a joint model comparison using several of the world's preeminent IAMs in order to support the Paris Agreement. Projections from these models are available from the IPCC WGIII Scenario Database. For more information, see IPCC 2014b.

[13] See the UNFCCC nationally determined contributions (NDC) Registry.

[14] All scenarios have identical assumptions on population growth, which has the global population growing from nearly 7 billion in 2010 to 9.5 billion by 2050. The subsequent paragraphs highlight the main assumptions across scenarios.

Table 2: Overview of scenarios

Scenario	Description
Business as usual	No further action to limit global warming is taken. Emissions rise unabated and lead to a substantial rise in average global temperatures
Nationally determined contributions (NDCs)	Beginning in 2020, countries act according to their pledges under the Paris Agreement (see **Table A3.1** in **Appendix 3).** They reduce global warming, but their actions are not enough to limit warming to an additional 2°C above pre-industrial levels by 2100.
2°C (consistent)	Countries act to limit global warming to 2°C by 2100.
2°C (delayed action)	Countries act to limit global warming to 2°C by 2100, but the action does not begin until 2030.

The trajectories of global GHG emissions in each of the four scenarios are presented in **Chart 2**. For comparison, the emissions paths from this study are mapped onto those provided in the IPCC WGIII AR5 scenario database.[15] Further, the IPCC scenarios are grouped into likely temperature ranges for context. A detailed description of each scenario is provided below, while the specific policies used for integrating the NDCs to the Paris Agreement in the EPPA model are found in **Table A3.1** in **Appendix 3**. We present the resulting policy and sectoral implications in the following section.

Baseline scenario—business as usual

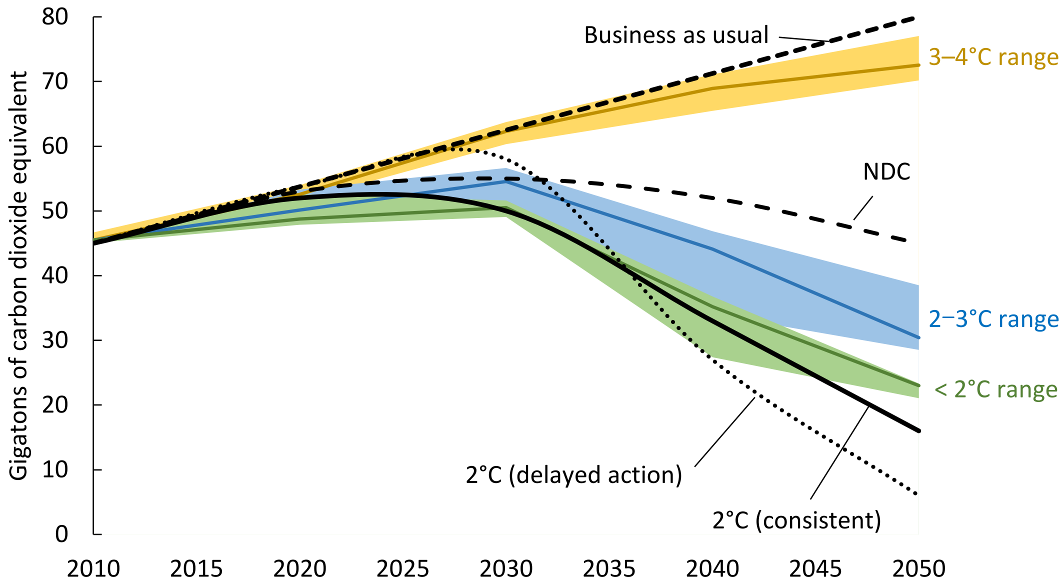
Under this scenario, carbon prices do not increase markedly from their current levels because no further meaningful action is taken to limit global warming. Emissions rise along with global growth in an unconstrained way, leading to a substantial rise in the global average temperature. This scenario could be considered business as usual and consistent with current policies, as less than 5 percent of GHG emissions globally are priced in line with Paris Agreement targets (World Bank Group 2019). Global annual emissions rise by nearly 80 percent by 2050, from 45 $GtCO_2e$ in 2010 (**Chart 2**)—on pace to push warming to exceed 4.0°C by 2100 (Vandyck et al. 2016).

The business-as-usual scenario serves as a benchmark and builds on several data sources and assumptions worthy of mention. First, near-term GDP growth projections are based on the IMF's World Economic Outlook (IMF 2013), while growth to mid-century is based on data from the World Bank (2013) and United Nations (2013). The GDP path in the business-as-usual scenario does not consider the effects of climate change. Second, the main data sources for energy use and energy intensity are from the International Energy Agency's World Energy Outlook (IEA 2012). For later years, energy-use levels are determined endogenously by factors such as patterns of economic growth, technological change and relevant energy or emissions policies. Third, emissions related to land use, land-use change and forestry (LULUCF) are calibrated consistent with RCPs (Riahi, Gruebler and Nakicenovic 2007). Non-carbon dioxide GHGs are also included in the model and are converted to their relative global warming potentials (GWPs) to translate them to carbon dioxide equivalents. Fourth, the business-as-usual scenario assumes no additional climate

[15] Data for scenarios reviewed in the *Fifth Assessment Report* (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC) are available at the Science for Global Insight AR5 Scenario Database.

policies over the projection and leads to a continued trend of increased emissions through the mid-century—putting climate change on a path to exceed 4°C by 2100.

Chart 2: Global greenhouse gas emissions in the four scenarios



Note: The shaded areas represent the 20th and 80th percentile (median value as darker line) per temperature range of scenarios included in the IPCC WGIII AR5 Scenario Database. Temperature ranges are based on emissions profiles with at least 50 percent probability of staying within the indicated temperature range.

Nationally determined contributions (NDCs) scenario

Ahead of joining the Paris Agreement, countries publicly outlined the climate actions they would take after 2020 under the new agreement. These actions are known as nationally determined contributions (NDCs). In this scenario, we assume countries fully meet their NDCs.[16]

For this, we first collected country-level pledges according to their NDCs[17] and then translated them into emissions targets and implemented them into the model via country-specific economy-wide carbon prices. Further, we assume that the carbon pricing is revenue neutral, with taxes returned to households in the form of lump-sum rebates. The NDCs we run with EPPA are summarized into EPPA country/regions in **Table A3.1** in **Appendix 3**.

A majority of the NDCs specify targets only to 2030, but we assume continued efforts to mitigate climate change through to 2050. For this, we carry forward the implied trend in the annual rate of change of emissions intensity at the country level.

Follow-through on the NDC pledges is estimated to have a material impact on global emissions. Here, emissions are estimated to peak around 2030, before falling to around their 2010 levels in 2050 (**Chart 2**). By 2050, annual emissions are 45 percent lower than in the business-as-usual scenario. Estimates from

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[16] Actions considered does not include a proposed Green Climate Fund (a climate financing mechanism under the UNFCCC) due to lack of details on this proposal (Vandyck et al. 2016).

[17] We collected these from the UNFCCC NDC Registry.

our EPPA model-based calculations also confirm a well-covered issue that current NDC pledges are insufficient to meet Paris targets of limiting warming to no more than 2°C by 2100.[18]

2°C (consistent) scenario

The 2°C (consistent) scenario considers a pathway of global GHG emissions that is likely to be consistent with limiting the increase in global temperatures to 2°C by 2100, compared with levels observed during the period of 1850–1900. Relative to the NDC scenario, additional climate policies are needed.

Regional contributions are calculated from their proportional NDC pledges—scaled to be consistent with the 2°C target. These are translated into emissions targets and implemented into the model via country-specific, revenue-neutral carbon prices.[19] Global emissions reductions consistent with this objective begin in 2020—the first binding year of the Paris Agreement.

As illustrated in **Chart 4**, global emissions estimates from EPPA are largely in line with limiting temperature change to 2°C and are similar to a 2°C consistent emissions path as outlined by the IPCC.[20] Here, global annual emissions fall by around 63 percent from 2020 to 2050, or by an average annual amount of 2.1 percent.

2°C (delayed action) scenario (abrupt transition)

Under this scenario, global warming is limited to the 2°C target, but policy actions are more heavily concentrated in later years. Specifically, it is assumed that countries fail to successfully act on their NDC pledges from 2020 to 2030 and then adopt stricter mitigation efforts in order to still limit warming to no more than 2°C.[21] Targets are achieved by raising country-specific, revenue-neutral carbon prices.

In this case, global annual emissions fall by around 87 percent from 2030 to 2050 (**Chart 2**), or by an average annual amount of 4.4 percent. In effect, delayed action on Paris Agreement commitments requires a doubling of the pace of mitigation over a standard 2°C scenario.

Results

The results of the four illustrative scenarios are presented below. First, we provide an overview of the policy variables (carbon prices) under the different scenarios, followed by a discussion of economic impacts. We then translate these results into a risk framework in the discussion section.

It is important to keep in mind that the main model used in this study, EPPA, does not incorporate the benefits of climate policy for the economy. Thus, negative impacts on GDP from policy actions, and the sectoral impacts outside of the fossil-fuel industry, are higher than they would be if the benefits of climate policy were considered (Ricke et al. 2018). The results from EPPA should therefore not be considered as a cost-benefit analysis of climate-policy action; they are instead intended to lead to a better understanding

[18] For more information, see United Nations (2018).

[19] This study assumes participation of all countries with existing pledges as outlined in the UNFCCC NDC Registry, including countries that have voiced plans to exit the Paris Agreement, such as the United States and Brazil.

[20] The 2°C emissions path used in this study is similar to the 430–480 ppm CO_2e (2100 concentration) scenario. For reference, see Table SPM1 from IPCC 2014b.

[21] We assume that the additional actions taken by each country are proportionate to their NDC pledges.

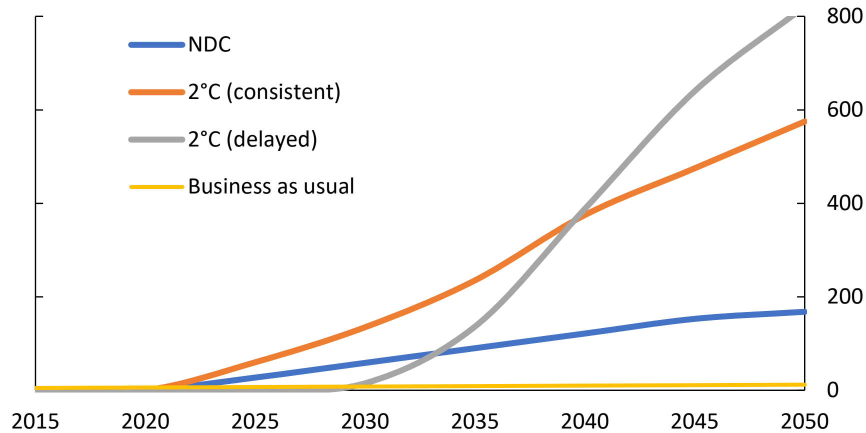
of transition risks. The assessment of the costs and benefits of climate policy requires an integrated modelling framework; we highlight some results from such a model in **Box 2**. Although results using integrated models are not our focus here, they suggest that the benefits of action on climate change may outweigh the costs.

Policy variables

The trajectory of global carbon prices under each scenario is presented in **Chart 3**. EPPA converts the emissions targets outlined in each scenario into country-specific carbon prices and applies them as a revenue-neutral tax on emissions. First, carbon prices rise materially to reduce emissions. Under the NDC scenario, EPPA calculates that carbon prices may need to rise to nearly US$200 per tonne of carbon dioxide equivalent by mid-century to be consistent with country-level NDC emissions pledges under the Paris Agreement (see **Appendix 3**). Given the NDC pledges are not consistent with 2°C target levels, EPPA estimates carbon prices must rise further in order to limit warming to 2°C. For the same temperature target, delaying action requires a sharper and stronger rise in carbon prices, with a notably higher level in 2050. This reflects that delayed policy actions must compensate for the past rise in emissions that have accumulated in the atmosphere.

Chart 3: Estimated carbon prices from the Economic Projection and Policy Analysis model

Dollars per carbon dioxide equivalent tonnes



There are several caveats to the carbon prices presented in **Chart 3**. Uncertainties about input data present continuous challenges. Consumer preferences may change; and the development of socio-economic variables such as income and population remain highly uncertain yet plays an integral role in driving the forecasts in CGE models like EPPA. Further, the discovery of new technologies that make it cheaper to reduce emissions will inevitably alter the carbon price trajectories presented here (see **Box 3**).

Economic variables

In this section, we first provide an overview of the impacts on overall GDP and different sectors of the economy under the business-as-usual baseline scenario, followed by the scenarios that model steps toward a lower-carbon economy. The global GDP figures of the business-as-usual scenario are based on data from the literature and not our calculation.

GDP impacts of higher temperatures

Consistent with other estimates, projections from DICE, the integrated assessment model (see **Box 2**), suggest that the world is on track to warm by 4.1°C if no further actions are taken to reduce emissions (**Chart 4**) (Nordhaus 2017). The baseline scenario of business as usual therefore suggests the possibility of significant economic costs, as the literature suggests nearly a one-for-one relationship between global warming and output losses (**Chart 5**). This is because higher temperatures have been shown to adversely affect several channels of the economy, including labour productivity (Day et al. 2019), agricultural yields (Schlenker and Roberts 2009) and industrial output (Burke, Hsiang and Miguel 2015). The economic impacts from climate change could also be much larger as a result of possible cliff or threshold effects (as shown in **Chart 2-A**, **Box 2**) (Lemoine and Traeger 2016).

Box 2: Estimated benefits of mitigating climate change

Given that EPPA is unable to capture the economic benefits from mitigating the physical costs associated with climate change, we turn to the DICE model to inform our business-as-usual scenario where no policy action is taken.

The DICE model—a preeminent IAM developed by 2018 Nobel prize winner William Nordhaus—integrates aspects of the macroeconomy, carbon cycle and climate science (see **Appendix 2** for full details). This framework allows for a weighing of the costs and benefits for the economy and social welfare of mitigating climate change.

DICE modifies a Ramsey-type growth model to estimate how the global economy produces emissions as a by-product of economic activity. Emissions, in turn, contribute to rising temperatures. Higher temperatures pose an economic cost to the economy through reduced output, which affects consumption prospects. The model estimates how mitigation actions can reduce emissions at some economic cost to current output.

Under the standard DICE model, damages from global warming hit US$30 trillion per year by 2100 (over 4 percent of GDP). But this calibration is based on studies of the effects of past warming on the economy. Other calibrations that include possible cliff effects or non-linearities from significantly more damages as temperatures increase suggest substantially higher amounts, up to 50 percent loss of annual GDP by 2100 (**Chart 2-A**).

Chart 2-A: **Economic damages from temperature change**

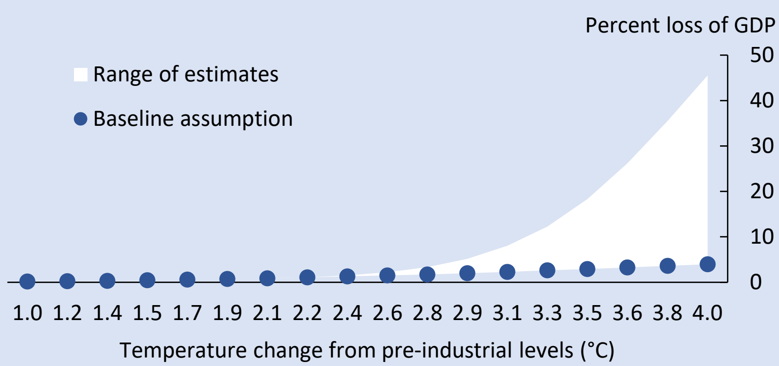


Chart 4: Current baseline trajectory shows steady warming

Change of surface temperature from pre-industrial levels

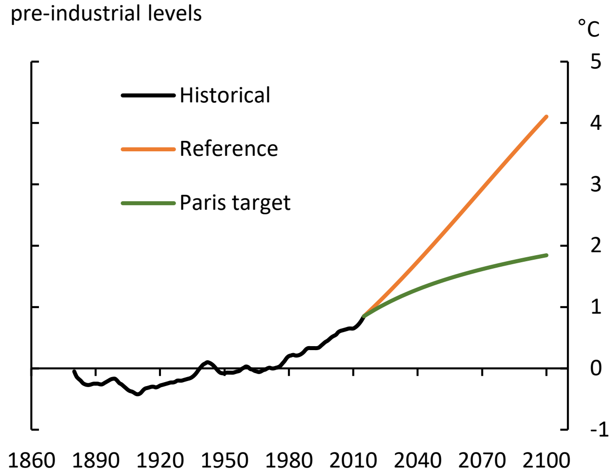
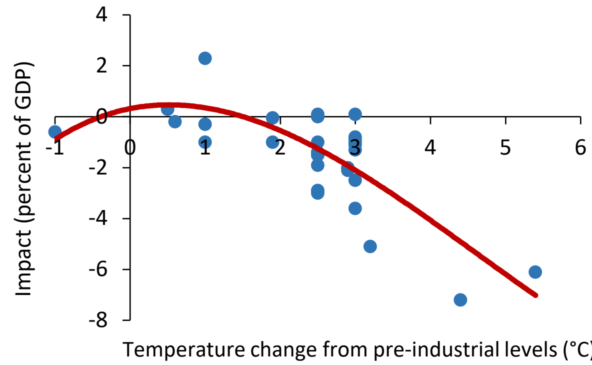


Chart 5: Literature synthesis of the global annual impact of climate change on GDP



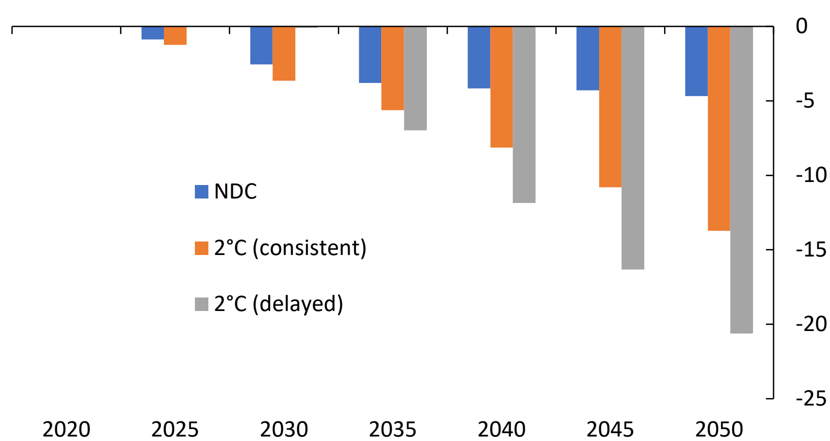
Note: The blue dots represent individual estimates from the literature of the GDP impact of rising temperatures from pre-industrial levels adapted from Tol (2018), supplemented with additional sources; see Appendix 4. The red line is a quadratic trendline.

GDP impacts from moving to a low-carbon economy

Mitigation costs are calculated as the policy-induced change in GDP as compared with the estimated GDP from the business-as-usual scenario. Within EPPA, climate-mitigation costs rise along with policy targets (**Chart 6**), as would be expected. It is estimated that the NDC scenario costs rise alongside temperature targets and lead to a 4 percent reduction in annual GDP by 2050. Delaying 2°C consistent action until 2030 results in higher GDP growth from 2020 to 2030, at which point carbon taxes are introduced at an accelerated pace. This scenario requires the most extreme structural transformation of the economy with the largest sectoral shifts and GDP declines, both of which happen over a shorter time period.

Chart 6: Estimated change in GDP in the Economic Projection and Policy Analysis model (excluding benefits from mitigation)

Percent of GDP of business-as-usual scenario



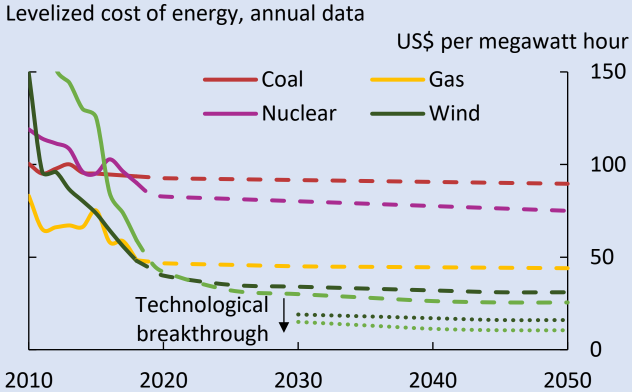
Box 3: Technology assumptions are important for the results

The scenarios used in this paper are based on the standard technological assumptions used in EPPA. For example, **Chart 3-A** shows that the standard expected cost declines for renewable technologies.

Varying these assumptions shows that shifts in technology could have important implications for scenario results and the future paths for the economy and climate. In this paper we do not provide a comprehensive analysis of the role of technology. But to underscore technology's importance and to motivate future work, we consider a scenario where wind and solar prices fall sharply—by an additional 50 per cent in 2030 **(Chart 3-A)**. This innovation could happen endogenously or through subsidy incentives or a market reaction to carbon pricing.

Chart 3-A: **Expectations of declining renewable energy costs**

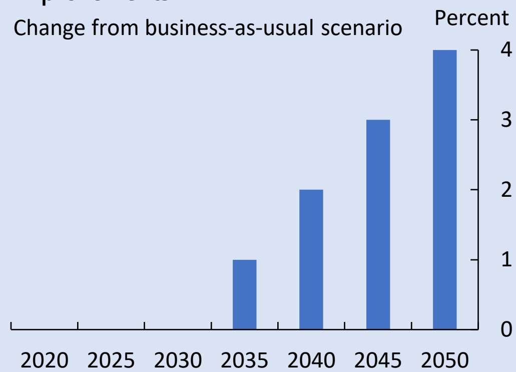
Levelized cost of energy, annual data



Note: The solid lines are historical prices; bar lines are baseline prices; dotted lines are potential decline in prices for wind and solar from a hypothetical technological breakthrough.

Chart 3-B: **Impact on GDP of technological improvements**

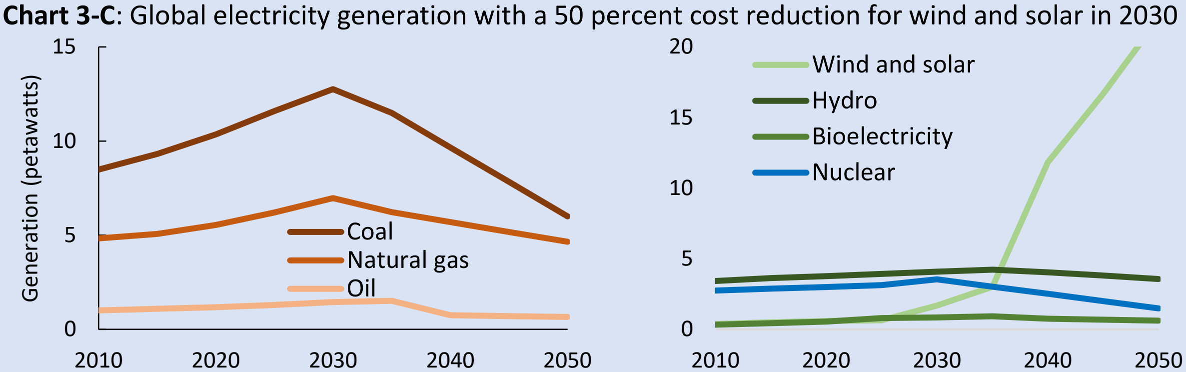
Change from business-as-usual scenario



We see two primary effects from this illustrative example. First, this technological improvement acts as a positive supply shock to the economy, boosting GDP (**Chart 3-B**). Second, not all sectors benefit. Fossil fuel industries experience a sharp decline in market share (**Chart 3-C**).

Other types of technological changes could have quite different effects—for example, if the costs of carbon capture and storage (CCS) fall by more than expected, it could lead to *more* fossil fuel production than assumed in the model. These differences suggest that future work to test the range of technological assumptions in models like EPPA would provide better understanding of the role of technology with respect to climate-related risks.

Chart 3-C: Global electricity generation with a 50 percent cost reduction for wind and solar in 2030



There are several caveats to the GDP estimates presented in **Chart 6.** Simulations in models like EPPA can vary due to a number of uncertainties related to the assumed structural parameters of the model. These include long-term productivity growth (which in turn affects the economic growth), population growth and technological advancements. **Box 3** shows how different rates of progress in technological advancements also affect the results. In fact, the actual cost of climate policy may prove to be lower than those provided by EPPA when we add factors beyond the scope of the model into the analysis. For example, the reallocation of capital to green investments could have positive growth effects beyond what is embedded in the model (Batten, Sowerbutts and Tanaka 2016).

Sectoral Impacts

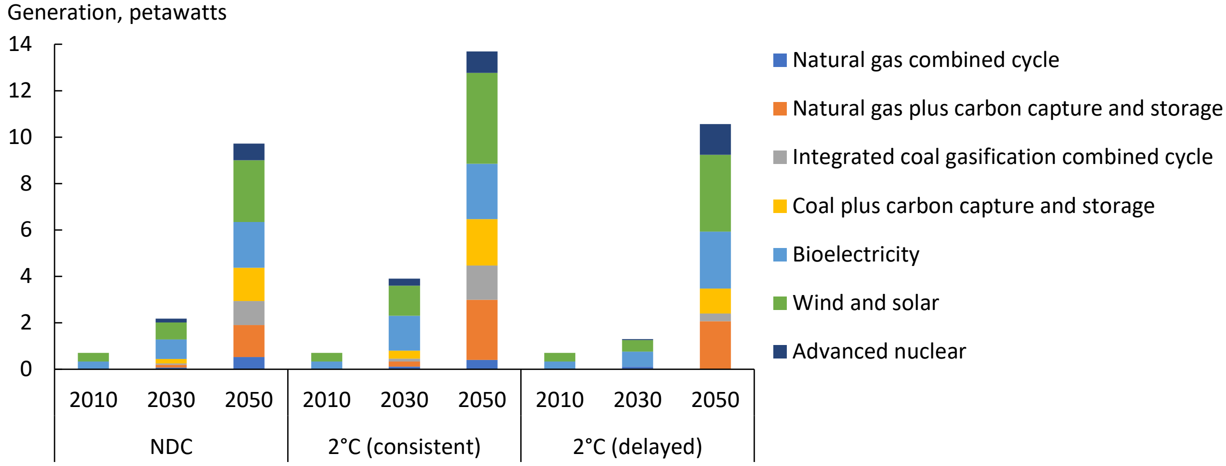
This sub-section decomposes aggregate global economy results on a sector-specific basis. **Table 3** provides detailed reporting of output, employment and capital stocks by sector.

A first observation is that we see reductions in output, employment and capital levels in the traditional fossil-fuel sectors as a result of climate-change mitigation. The underlying explanation is that higher charges lead to more efficient uses of energy and a shift in the composition of fuel consumption. Energy efficiency also weighs on electricity demand, which results in less output, employment and capital in the electricity generation sector.

Second, we see some offsetting gains in fossil-fuel production that uses CCS (**Chart 7**). Other advanced low- and zero-carbon technologies also come into play over time. Among the transition scenarios, an early 2°C pathway leads to the biggest increases in new and advanced technology sectors, as it provides the strongest pricing incentives to the market, along with time for these industries to gain market share.

Chart 7: Contribution of technological progress to sectoral shifts

Generation, petawatts



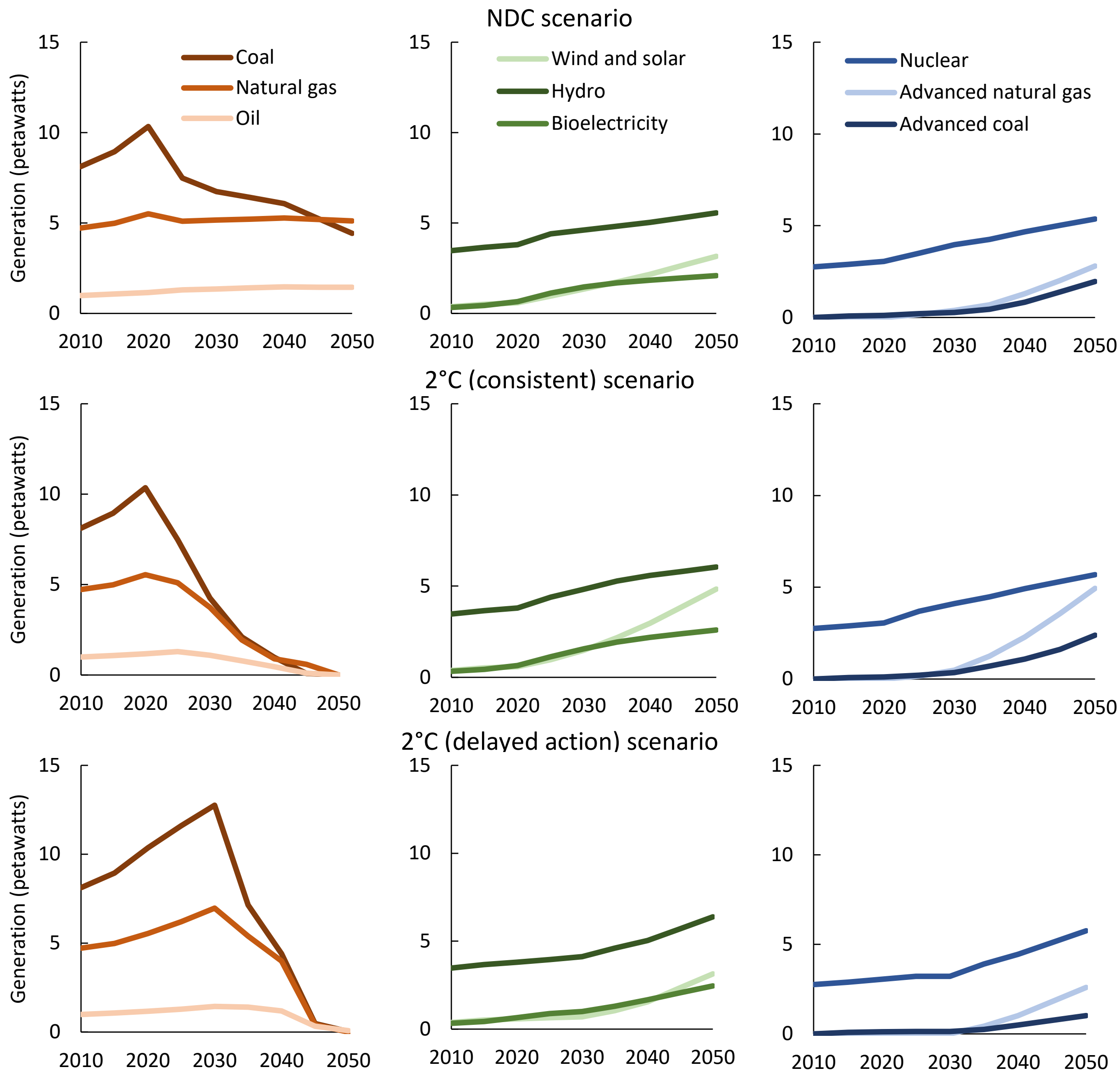
Third, we see a shift of workers across sectors in **Table 3**. Some of the employment losses from traditional fossil-fuel sectors are absorbed within other industries (e.g., forestry, agriculture, transportation and other). It is worth noting that this may result in adjustment costs to households that are not captured in the model, given rigidities in the labour market (e.g., retraining, moving). This would also raise personal challenges for those affected. As expected, the smallest impacts are seen in sectors that rely the least on fossil fuels, including services and dwellings.

Table 3: Change in global output, employment and capital from levels in the business-as-usual scenario

	Significance as percent of global	NDC		2°C (consistent)		2°C (delayed)	
		2030	2050	2030	2050	2030	2050
		Output (change from business as usual, percent)					
Crop	1.9	0.0	-1.9	0.0	-7.7	0.0	-9.8
Livestock	1.3	-0.7	-2.4	-0.8	-7.8	0.0	-6.6
Forestry	0.2	-0.9	-1.1	-1.0	5.5	0.0	-4.8
Coal	0.2	-27.6	-21.8	-33.1	-62.6	0.0	-72.0
Oil	1.6	-4.9	-9.0	-5.8	-33.8	0.0	-50.4
Refined oil	2.8	-12.4	-18.8	-14.8	-47.3	0.0	-65.8
Natural gas	0.5	-17.8	-27.1	-21.4	-54.3	0.0	-72.0
Electricity	1.9	-11.5	-17.8	-13.7	-34.5	0.0	-50.2
Energy intensive	12.5	-2.5	-3.8	-3.1	-12.5	0.0	-19.1
Other	24.9	-0.8	-1.5	-1.0	-5.6	0.0	-8.5
Services	43.6	-1.2	-1.0	-1.5	-3.2	0.0	-3.8
Transportation	5.5	-1.6	-2.0	-1.9	-5.4	0.0	-7.6
Dwelling	3.1	-0.1	-0.7	-0.2	-2.1	0.0	-3.7
		Employment (change from business as usual, percent)					
Crop	1.6	5.6	3.2	6.7	23.8	0.0	28.6
Livestock	0.8	4.8	2.5	5.8	26.5	0.0	44.3
Forestry	0.2	6.6	5.1	7.9	30.8	0.0	34.5
Coal	0.2	-34.2	-26.2	-82.0	-64.9	0.0	-66.1
Oil	0.6	-5.5	-12.8	-13.2	-34.8	0.0	-34.1
Refined oil	0.2	-9.7	-17.5	-23.3	-43.2	0.0	-42.1
Natural gas	0.3	-18.2	-31.0	-43.6	-56.0	0.0	-60.6
Electricity	0.1	9.5	-20.5	22.7	-68.7	0.0	-42.3
Energy intensive	4.7	-3.6	-3.3	-8.7	-34.8	0.0	-47.1
Other	21.2	0.4	-0.3	0.4	-2.1	0.0	-4.8
Services	67.2	-0.3	-0.1	-0.4	-0.4	0.0	-3.0
Transportation	2.6	10.3	6.3	12.3	27.0	0.0	28.6
Dwelling	0.4	1.6	0.7	1.9	2.8	0.0	-1.3
		Capital (change from business as usual, percent)					
Crop	0.9	1.1	0.1	1.4	14.9	0.0	18.8
Livestock	0.5	1.7	1.1	2.0	9.4	0.0	31.1
Forestry	0.2	3.3	6.6	3.9	28.9	0.0	35.0
Coal	0.2	-37.1	-27.1	-89.1	-66.4	0.0	-67.4
Oil	3.8	-7.4	-14.4	-17.8	-40.3	0.0	-44.3
Refined oil	0.5	-8.2	-16.5	-19.6	-44.5	0.0	-46.3
Natural gas	1.1	-20.9	-31.5	-50.1	-56.6	0.0	-60.0
Electricity	0.2	-3.7	-27.0	-8.8	-69.0	0.0	-44.0
Energy intensive	5.6	-0.5	-0.4	-0.6	-6.9	0.0	-7.4
Other	17.5	-1.6	-2.2	-2.0	-7.5	0.0	-11.5
Services	53.5	-2.2	-1.9	-2.7	-6.1	0.0	-7.0
Transportation	3.1	5.6	2.2	6.7	9.1	0.0	13.4
Dwelling	12.7	-0.3	-0.8	-0.3	-2.6	0.0	5.3

Finally, looking across scenarios we see a greater reallocation across sectors as climate policy strengthens, with greater effects on output, employment and capital stocks. At the same time, the pace at which policies are introduced matter. In line with the results shown in **Table 3**, a delayed transition leads to the biggest swings in capital in the resources sector and over the least amount of time, raising the costs borne by fossil-fuel producers and workers.

Chart 8: Global electricity generation across scenarios by source from 2010 to 2050.



Next, we take a deeper look at the transformation within the electricity-generating sector. **Chart 8** depicts the estimated pathways of global electricity generation by type across scenarios. Traditional fossil fuels are in the first column, renewables in the second, and advanced technologies (e.g., nuclear and advanced fossil-fuel) in the third. Under each scenario, fossil-fuel generation sharply declines from current levels. Of course, this change is more pronounced under stronger climate policies. Compared with the NDC scenario, a full move to a 2°C pathway leads to a more substantial reduction in fossil fuels in favour of additional renewable capacity as well as the introduction of advanced technologies like CCS. This implies that the introduction of certain advanced technologies lowers emissions and helps to sustain the use of fossil fuels as an input in electricity generation.

The transformation of the electricity sector is sensitive to the pace of climate policy. The 2°C scenario with delayed action estimates a similar removal of conventional fossil-fuel generation, but in half the time. This increases the risk of stranded assets because (i) utilities now have a shorter economic adjustment period and (ii) more adjustment is needed to compensate for the continued buildup of capital until 2030.

Next, we look at potential implications for global oil markets. Under the 2°C (consistent) scenario we observe a gradual reduction in the supply of oil (**Chart 9**). A growing share is produced using CCS technologies, helping to offset the declines in traditional production (**Chart 9**). Meanwhile, delaying the introduction of 2°C consistent policies until 2030 results in a much more drastic reduction in the supply of oil and an increased risk of stranded assets, given a sharper fall in capital over a shorter time period (**Chart 10**).

Chart 9: **Global supply of oil**

Global index (2015 = 100)

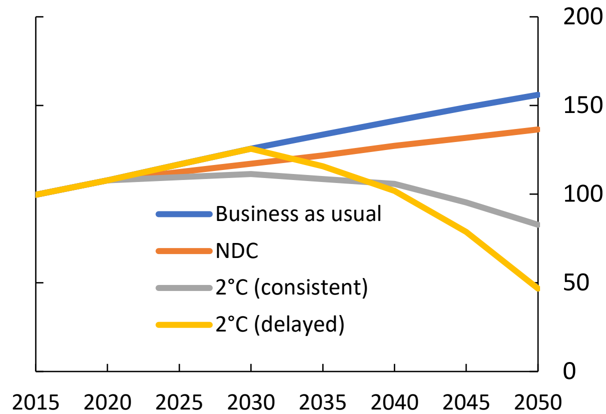
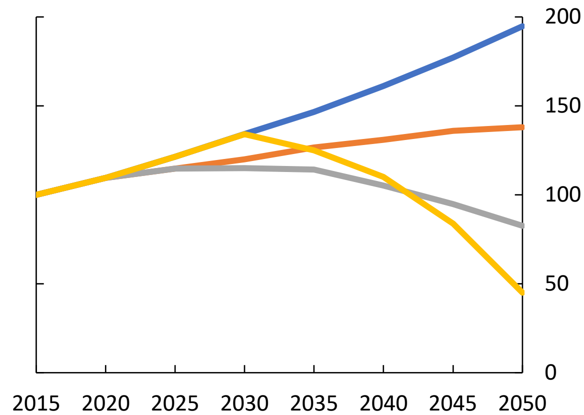


Chart 10: **Capital in the global oil sector**

Global index (2015 = 100)



Robustness check

As a robustness check, we compared the estimated carbon price, GDP and emissions relationships from this study with estimates from the IPCC's AR5 (**Chart 11** and **Chart 12**).[22] The black dots represent estimates for the NDC scenario and 2°C consistent scenario from this study, smaller dots represent individual model estimates from the IPCC's AR5, and the red line is a linear trend relationship.

Our results show broadly similar estimates for carbon prices, as well as their relationship with emissions reductions by 2030 (**Chart 11**). Estimates from the IPCC's AR5 show carbon prices of about US$75 per tonne of carbon dioxide equivalent by 2030, leading to a 20 to 30 percent emissions reduction—consistent with 2°C warming trajectory. The emissions reduction estimated in this study is within this range and is largely consistent with the 2°C pathway. However, this study implies that somewhat higher carbon prices by 2030 are needed to achieve this because (i) business-as-usual emissions are slightly higher in EPPA as compared with many of those housed within the IPCC estimates and (ii) the IPCC reference scenarios assume earlier mitigation action, as can be seen in **Chart 2**.

[22] Projections from these models are available from the IPCC WGIII Scenario Database.

Chart 11: Comparison of relationship between carbon prices and emissions reduction, 2030

Smaller dots represent seperate model estimates from the IPCC WGIII Scenario Database

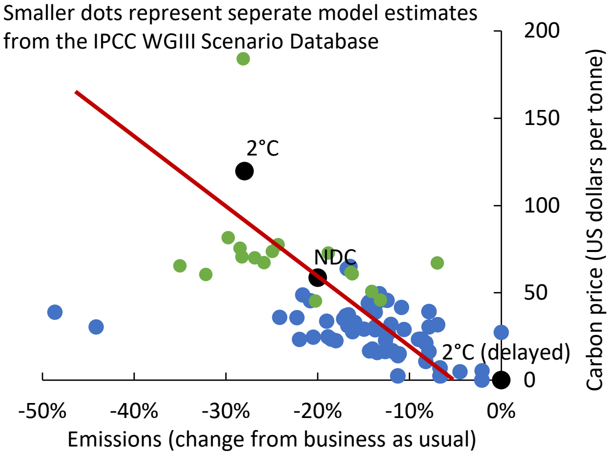
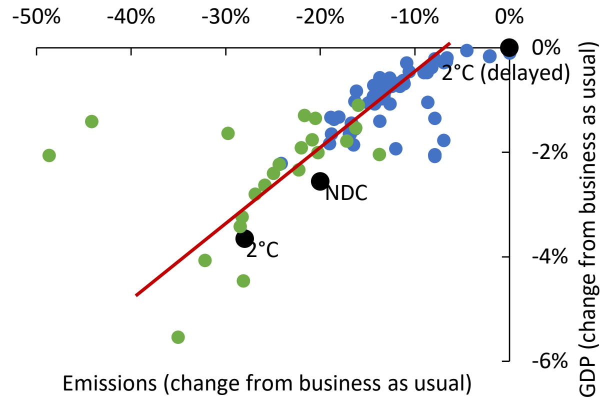


Chart 12: Comparison of relationship between GDP and emissions reduction, 2030

Smaller dots represent seperate model estimates from the IPCC WGIII Scenario Database



Next, we compare our estimated GDP impacts with benchmarks from the IPCC's AR5 (**Chart 12**). Estimates from this study are broadly in line with those from the IPCC WGIII Scenario Database. But as noted above, EPPA estimates that more mitigation is required to achieve the 2°C target (as compared with the business-as-usual scenario), which may lead to a larger impact on GDP as compared with estimates from the IPCC WGIII Scenario Database. Additionally, these estimates do not assume that the lowest-cost mitigation policies are pursued globally, which could lead to higher estimated costs.

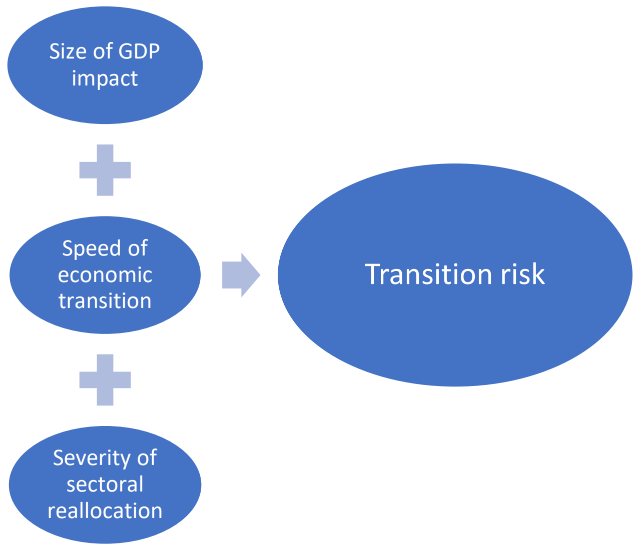
Discussion and future work

The results show significant economic implications from climate change and the transition to a low-carbon economy. The timing and magnitude of global GDP and sectoral impacts, among other outcomes, vary considerably under the mix of scenarios.

To get a better understanding of the risks from these different paths, we evaluate the potential transition risks to the financial system along three metrics, as seen in **Figure 3**:

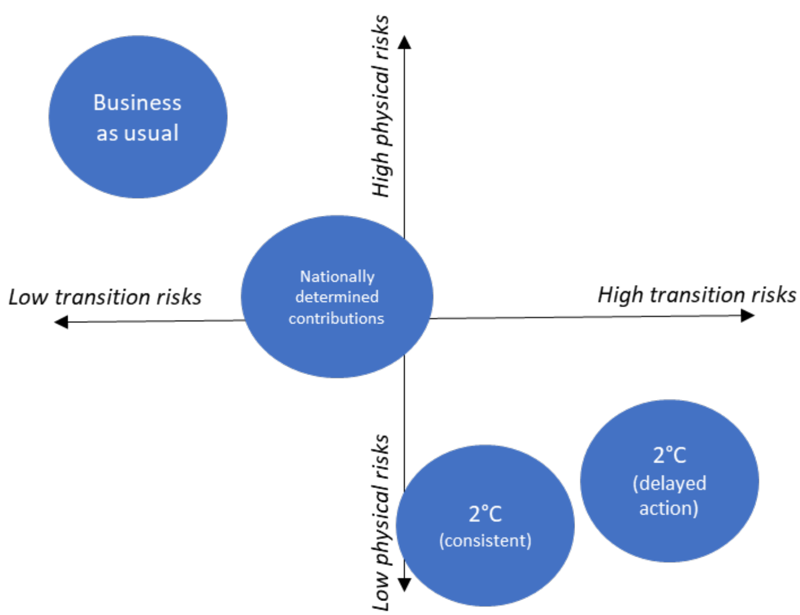
- **Size of the impact on GDP**. All else being equal, the larger the negative impacts on GDP, the greater the costs (and risks) posed by the shift in climate policy.
- **Speed of the impacts on the economy**. Under the scenarios where policy action is taken on climate change, transition risks increase with shorter transition periods—as in the case of the delayed 2°C scenario. This is because agents have less time to adapt, and technological offsets to the decline in fossil-fuel production (e.g., cheaper renewable sources of energy) have less time to develop.
- **Severity of the reallocation of capital and labour**. Greater swings in capital and labour across sectors increase the likelihood of financial sector losses through channels such as stranded assets and rises in frictional unemployment.

Figure 3: Metrics for evaluating transition risks



In addition, we use the rise in mean temperature as a proxy for the impact on the financial system coming from physical risks, given its association with more frequent and severe weather events. These simple metrics suggest a relative ranking of the scenarios along both physical and transition risks, as can be seen in **Figure 4**.

Figure 4: Illustrative scenarios show a range of physical and transition risks



The illustrative scenarios suggest some trade-offs between physical and transition risks. The business-as-usual scenario sees no shift away from the current reliance on traditional fossil fuels, but unchecked warming leads to the maximum physical risks. Under the NDC scenario, a transition takes place, but it is below what is needed to meet Paris targets and to significantly reduce physical risks. To meet the objectives of the Paris Agreement, a larger structural change to the global economy is required; this, however, minimizes physical risks. The pace with which these policies are introduced also matters, as delaying action could exacerbate transition risks (and raise near-term physical risks). Given the high level of uncertainty regarding future developments, the distribution of risks should be evaluated across a range of plausible futures.

In sum, the results suggest that while transition risks can be avoided through inaction, this comes at significant economic costs through higher physical damages and risks. Finally, action that comes late must be more abrupt to keep temperature increases in check, raising transition risks. These risks touch on the interests of a broad-range of stakeholders across the private and public sectors. In addition to central banks and governments, these risks could affect financial institutions, resource-intensive industries and other private sector firms. As such, public and private sector institutions may need to step up their analysis of these risks.

Further improvements in scenario analysis, as well as wider-spread use across the public and private sectors could lead to a better understanding of the physical and transition risks and opportunities of climate change. Future work would benefit from building on this study's scenarios and models.

In terms of the **scenarios,** a broader set of standardized scenarios is needed. In this respect, the NGFS, a group of central banks that collaborates on better understanding climate risks, will help build the intellectual expertise. The development of systematic approaches for generating scenarios could help better ensure that the full range of risks is being considered. At the country level, further research could combine more granular regional and sectoral impacts from scenario analysis with financial stress-testing techniques to get a better sense of potential financial system impacts. A more comprehensive look at the role of technology would also be useful. The development of local-level physical risk scenarios would also help overcome the limitations of the damage functions found in IAMs for assessing acute financial system risks.

In terms of the **models**, adding monetary and fiscal policy, as well as financial system links, would be useful to better understand policy implications. Endogenizing productivity growth would help to clarify the long-run impacts of climate change on growth. Improvements could also be made in the simulation of structural changes. The possibility of non-linearities is also a challenge. Better knowledge of potential non-linearities related to the physical environment (e.g., an accelerated pace of hurricane damage as temperatures rise) or in the economy (e.g., larger declines in labour productivity as temperatures rise) would be welcome. Finally, future studies could examine specific weather "shocks" that would be disruptive to the financial system and capital stock, alongside balance-sheet-level analysis. This contrasts with the models used in this paper; these are better suited to analyze transition risks, as damage from climate change is modelled to accrue steadily.

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Appendix 1—MIT Economic Projection and Policy Analysis (EPPA) model

This work used an updated version of the model—EPPA6 (Chen et al. 2015). This is a multi-region and multi-sector recursive dynamic CGE model of the world economy. The recursive approach suggests that production, consumption, savings and investment are determined by current period prices. Capital for the next period's production is formed by savings supply funds for investment along with investment plus capital remaining from previous periods. Labour endowment grows at a pre-determined rate influenced by population and productivity growth rates.

The model is formulated in a series of mixed complementary problems set for the three types of agents in each region: households, producers and government. In their simplest form, the key optimizing behaviour and equilibrium conditions in EPPA may be summarized as follows:

1. *Zero-profit conditions*

Zero-profit conditions represent cost-benefit analyses for economic activity. The zero-profit condition expressed MCP format is

$$MC - MB \geq 0; Q \geq 0; [MC - MB] * Q = 0. \quad \text{(A1.1)}$$

2. *Market-clearing conditions*

For each market-clearing condition, the price level is determined based on market demand and supply. A typical market-clearance condition in MCP format is

$$S \geq D; P \geq 0; [S - D] * P = 0. \quad \text{(A1.2)}$$

3. *Income-balance conditions*

Income-balance conditions specify income levels of household and government that support their spending level. A typical income-balance condition in MCP format is

$$E \geq I; E \geq 0; [E - I] * E = 0. \quad \text{(A1.3)}$$

To demonstrate the consumer's preference, consider a utility function U with preference over N commodities indexed by i, where c_i, c_i^* and w represent consumption of commodity i, shift parameter for the consumption of commodity i and the budget, respectively. The utility function takes the form

$$u = U(c_1 - c_1^*, c_2 - c_2^*, \dots, c_N - c_N^*), \quad \text{(A1.4)}$$

where the income elasticity for the consumption of commodity i is defined as

$$\eta_i = \frac{c_i - c_i^*}{c_i} / \frac{w - \sum_{i=1}^{N} c_i^*}{w}. \tag{A1.5}$$

After the application of the Engel's Aggregation, it is possible to notice that for a given η_i, the solution for c_i^* that satisfies equation$(A1.5)$ is

$$c_i^* = (1 - \eta_i) c_i. \tag{A1.6}$$

From the third period onward, information from both the adjacent previous period $(t - 1)$ and the first period $(t = 0)$ is used to update c_i^* based on equation$(A1.6)$:

$$c_{i,t}^* = x_{i,t-1}^T - y_{i,t-1}^T * \frac{x_{i,t-1}^T - x_{i,0}}{y_{i,t-1}^T - y_{i,0}}; t \geq 2, \tag{A1.7}$$

where $(x_{i,0}, y_{i,0})$ is the base-year consumption bundle, y_i represents the aggregation of all commodities other than x_i, and $(x_{i,t-1}^T, y_{i,t-1}^T)$ is the imputed consumption bundle derived from the given income elasticities and the budget w_{t-1} using the base-year relative price level.

In EPPA6, all savings are used as investment, which meets the demand for capital goods. The capital is divided into a malleable portion, KM_t, and a vintage non-malleable portion, $V_{n,t}$. The dynamics of the malleable capital are described by

$$KM_t = INV_{t-1} + (1 - \theta)(1 - \delta)^5 KM_{t-1}, \tag{A1.8}$$

where θ is the fraction of the malleable capital that becomes non-malleable at the end of period $t - 1$, and INV_{t-1} and δ are the investment and depreciation rate, respectively.[23] The newly formed non-malleable capital $V_{1,t}$ comes from a portion of the survived malleable capital from the previous period:

$$V_{1,t} = \theta(1 - \delta)^5 KM_{t-1}. \tag{A1.9}$$

The model assumes that physical productivity of installed vintage capital does not depreciate until it reaches the final vintage. This reflects an assumption that a physical plant, once in place, can continue to produce the same level of output without further investment, whereas malleable capital depreciates continuously.

The increase in demand for the output of the backstop technology is accompanied by increasing investment in its operation, and so is the supply of the technology-specific input factor, which may eventually become a non-binding input for the operation of the backstop technology:

[23] The factor of 5 is used because the model is solved in five-year intervals.

$$bbres_{bt,t+1} = \alpha * \left[bout_{bt,t} - (1-\delta)^5 * bout_{bt,t-1}\right] + \beta\left[bout_{bt,t}^2 - (1-\delta)^5 * bout_{bt,t-1}^2\right] + bbres_{bt,t} * (1-\delta)^5, \tag{A1.10}$$

where $bbres_{bt,r,t}$ is the supply of technology-specific factor for technology bt in period t, and $bout_{bt,t}$ is the output of bt in period t.

Appendix 2—Dynamic Integrated Economy-Climate (DICE) model

The DICE model is an integrated assessment model that views climate change in the framework of a neoclassical optimal growth model modified to include climate investments (Nordhaus 2016). The model integrates the carbon cycle to the greenhouse-gas accumulations and the economic impacts (or damages) coming from climate change. This work used the DICE-2016R model.

The model optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption. Net output is gross output reduced by mitigation costs and damages:

$$Q(t) = [1 - D(t)][1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}, \tag{A2.1}$$

where $Q(t)$ is output net of damages and abatement, $\Lambda(t)$ represents the abatement cost function, $A(t)$ is total factor productivity of Hicks-neutral technological change, $K(t)$ is capital stock and services, and $L(t)$ is the labour force. These three last variables contribute to gross global output that can be divided between total consumption and total gross investment, where labour force is an exogenous proportion of the population, and capital accumulates according to an optimized savings rate.

$D(t)$ then represents the damage function, which can be interpreted as the economic impacts or damages of climate change, where

$$D(t) = \varphi_1 T_{AT}(t) + \varphi_2 T_{AT}(t)^2 + \varphi_3 T_{AT}(t)^{6.754}. \tag{A2.2}$$

The default DICE assumption is that $\varphi_1 = 0$, $\varphi_2 = 0.00236$ and $\varphi_3 = 0$. The "Weitzman" damage function modifies that assumed by Nordhaus and assumes a 50 percent reduction in global GDP due to a 6°C warming by 2100 (Nordhaus assumes that a 50 percent reduction in GDP occurs at 18°C). The "Dietz and Stern" approach assumes a 50 percent reduction in GDP occurs at 4°C warming by 2100—a warming within range of the DICE baseline (Dietz and Stern 2015). In the Dietz and Stern approach, damage function with a tipping point at $T_{AT} = 4$, $\varphi_3 = 0.000819$; whereas for the Weitzman models, a tipping point at $T_{AT} = 6$, $\varphi_3 = 0.0000507$.

Carbon dioxide emissions are given by a function of carbon intensity, economic activity and emissions reduction rate of the form

$$E(t) = \varepsilon(t)[1 - \tau(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} + E_{Land}(t), \tag{A2.3}$$

where $\varepsilon(t)$ is the current level of carbon intensity or the ratio of carbon dioxide to output, $\tau(t)$ is the emission reduction rate and $E_{Land}(t)$ is the exogenous land-use emissions.

These emissions are linked to the three reservoirs of the carbon cycle, radiative forcing and climate change and take place in the following geophysical equations:

$$M_j(t) = \phi_{0j}E(t) + \sum_{i=1}^{3} \phi_{ij}M_i(t-1), \tag{A2.4}$$

where the three reservoirs are $j = AT, UP, LO$, which are the atmosphere, the upper oceans and biosphere, and the lower oceans, respectively. The parameter ϕ_{ij} represents the flow parameters between reservoirs per period, where all emissions flow into the atmosphere.

The relation between greenhouse gas accumulation and increased radiative forcing is

$$F(t) = \lambda \left[log_2 \left(\frac{M_{AT}(t)}{M_{AT}(1750)} \right) \right] + F_{EX}(t), \quad \text{(A2.5)}$$

where $F(t)$ is the change in total radiative forcing from anthropogenic sources such as carbon dioxide. The first term gives the forcing due to atmospheric concentrations of carbon dioxide, whereas the second term, $F_{EX}(t)$, is the exogenous forcing:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\} \quad \text{(A2.6)}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)], \quad \text{(A2.7)}$$

where $T_{AT}(t)$ is the global mean surface temperature and $T_{LO}(t)$ is the mean temperature of the deep oceans.

Appendix 3—Integration of intended national determined contributions (NDC) to the Paris Agreement in the Economic Projection and Policy Analysis model

Table A3.1: Climate and energy policies relative to countries' NDC as implemented in the EPPA model

Country or region	2010 emissions (megatons)	2030 emissions (relative to 2010)	Carbon dioxide coverage	Energy policies implemented by 2030 (relative to 2010 levels)
Africa (AFR)	829	783 (94%)	All GHGs	*Egypt*: Increase renewables' share in power production up to 20% *South Africa*: Increase renewables' energy capacity
Australia and New Zealand (ANZ)	107	83 (77%)	All GHGs	*Australia*: Increase renewables' share in power production up to 20% *New Zealand*: Increase renewables' share in power production up to 90%
Higher-income East Asia (ASI)	634	553 (87%)	All GHGs	*Malaysia*: Increase renewables' share in energy capacity up to 10% *Thailand*: Increase share of renewables in primary demand up to 20%
Brazil (BRA)	411	213 (52%)	All GHGs	Increase renewables' energy capacity
Canada (CAN)	555	491 (88%)	All GHGs	Decrease private vehicle emissions down to 88g/km
China (CHN)	8501	9216 (108%)	CO_2	Increase non-fossil share in primary demand up to 15% and increase renewables' energy capacity
Europe (EUR)	4046	2837 (70%)	All GHGs	Increase share of renewables' in gross final demand up to 20% and decrease private vehicle emissions down to 95g/km
Indonesia (IDZ)	428	308 (72%)	All GHGs	Increase renewables' share in power production up to 19%
India (IND)	1700	3816 (224%)	All GHGs	Increase renewables' energy capacity
Japan (JPN)	1212	708 (58%)	All GHGs	Increase renewables energy capacity
Korea (KOR)	566	378 (67%)	All GHGs	Increase renewables' share in primary demand up to 5%
Middle East (MES)	1601	1664 (104%)	All GHGs	*Turkey*: Increase renewables' share in gross final energy consumption up to 20.5% and increase renewables' share in power production up to 30%
Mexico (MEX)	466	403 (86%)	All GHGs	Increase renewables' share in power production up to 35%
Rest of Asia (REA)	208	195 (94%)	All GHGs	*Vietnam*: Increase renewables' share in primary demand and power production up to 5%
Rest of Eurasia (ROE)	691	785 (114%)	All GHGs	*Ukraine*: Increase renewables' share in final consumption up to 11% and increase renewables energy capacity
Rest of Latin America (LAM)	642	639 (100%)	CO_2, CH_4	*Argentina*: Increase renewables' share in power production up to 8% *Chile*: Increase renewables' share in power production up to 20%
Russia (RUS)	1658	1602 (97%)	All GHGs	*No energy policies announced to be implemented by 2030*
United States (USA)	5701	4392 (77%)	All GHGs	Double the power production of wind, solar and geothermal energy and decrease private vehicle fuel consumption down to 54.5 miles/gallon

Note: Some NDC targets are conditional on receiving international financial support, technological transfer or capacity building. Conditional NDCs are retained for countries that announced them.

Appendix 4—Data sources

Table A4.1: Literature synthesis of the global annual impact of climate change on GDP (adapted from Tol 2018, supplemented with additional sources)

Study	Warming (°C)	Impact (% GDP)
d'Arge 1979	-1	-0.6
Nordhaus 1982	2.5	-3.0
Berz 1984	2.5	-1.5
Nordhaus 1991	3.0	-1.0
Nordhaus 1994a	3.0	-3.6
	6.0	-6.7
Nordhaus 1994b	3.0	-1.3
Fankhauser 1995	2.5	-1.4
Tol 1995	2.5	-1.9
Nordhaus and Yang 1996	2.5	-1.4
Plambeck and Hope 1996	2.5	-2.9
Mendelsohn et al. 2000	2.5	0.0
	2.5	0.1
Nordhaus and Boyer 2000	2.5	-1.5
Tol 2002	1.0	2.3
Maddison 2003	2.5	0.0
Rehdanz and Maddison 2005	0.6	-0.2
	1.0	-0.3
Hope 2006	2.5	-1.0
Nordhaus 2006	3.0	-0.9
	3.0	-1.1
Nordhaus 2008	3.0	-2.5
Pin and Xiaobing 2010	1	-1
Maddison and Rehdanz 2011	3.2	-5.1
Bosello et al. 2012	1.9	-0.5
Roson and van der Mensbrugghe 2012	2.9	-2.1
	5.4	-6.1
Nordhaus 2013	2.9	-2.0
Estrada et al. 2017	0.5	0.3
Kahn et al. 2019	1.9	-1
	4.4	-7.2
Lang and Gregory 2019	3	0.2

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